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(54) Title: METHOD AND APPARATUS FOR MEASURING AND REPORTING CHANNEL STATE INFORMATION IN A HIGH EFFICIENCY, HIGH PERFORMANCE COMMUNICATIONS SYSTEM

(57) Abstract: Channel state information (CSI) can be used by a communications system to precondition transmissions between transmitter units and receiver units. In one aspect of the invention, disjoint sub-channel sets are assigned to transmit antennas located at a transmitter unit. Pilot symbols are generated and transmitted on a subset of the disjoint sub-channels. Upon receipt of the transmitted pilot symbols, the receiver units determine the CSI for the disjoint sub-channels that carried pilot symbols. These CSI values are reported to the transmitter unit, which will use these CSI values to generate CSI estimates for the disjoint sub-channels that did not carry pilot symbols. The amount of information necessary to report CSI on the reverse link can be further minimized through compression techniques and resource allocation techniques.

METHOD AND APPARATUS FOR MEASURING AND REPORTING CHANNEL STATE INFORMATION IN A HIGH EFFICIENCY, HIGH PERFORMANCE COMMUNICATIONS SYSTEM

BACKGROUND OF THE INVENTION

I. Field of the Invention

The present invention relates to the field of communications. More particularly, the present invention relates to the measurement and report of channel state information in a high efficiency, high performance communications system.

II. Description of the Related Art

A modern day wireless communications system is required to operate over channels that experience fading and multipath. One such communications system is a code division multiple access (CDMA) system that conforms to the "TIA/EIA/IS-95 Mobile Station-Base Station Compatibility Standard for Dual-Mode Wideband Spread Spectrum Cellular System," hereinafter referred to as the IS-95 standard. The CDMA system supports voice and data communication between users over a terrestrial link. The use of CDMA techniques in a multiple access communication system is disclosed in U.S. Patent No. 4,901,307, entitled "SPREAD SPECTRUM MULTIPLE ACCESS COMMUNICATION SYSTEM USING SATELLITE OR TERRESTRIAL REPEATERS," and U.S. Patent No. 5,103,459, entitled "SYSTEM AND METHOD FOR GENERATING WAVEFORMS IN A CDMA CELLULAR TELEPHONE SYSTEM," both assigned to the assignee of the present invention and incorporated herein by reference.

An IS-95 system can operate efficiently by estimating channel parameters at a receiver unit, which uses these estimated channel parameters to demodulate a received signal. The IS-95 system makes channel estimation efficient by requiring the transmission of a pilot signal

from every base station. This pilot signal is a repeating PN-type sequence known by the receiver unit. Correlation of the received pilot signal with a local replica of the pilot signal enables the receiver unit to estimate the complex impulse response of the channel and adjust demodulator parameters accordingly. For the IS-95 waveform and system parameters it is not necessary or beneficial to report information on the channel conditions measured by the receiver unit back to the transmitter unit.

Given the ever-growing demand for wireless communication, a higher efficiency, higher performance wireless communications system is desirable. One type of higher performance wireless communications system is a Multiple Input/Multiple Output (MIMO) system that employs multiple transmit antennas to transmit over a propagation channel to multiple receive antennas. As in lower performance systems, the propagation channel in a MIMO system is subject to the deleterious effects of multipath, as well as interference from adjacent antennas. Multipath occurs when a transmitted signal arrives at a receiver unit through multiple propagation paths with differing delays. When signals arrive from multiple propagation paths, components of the signals can combine destructively, which is referred to as "fading." In order to improve the efficiency and decrease the complexity of the MIMO system, information as to the characteristics of the propagation channel can be transmitted back to the transmitter unit in order to precondition the signal before transmission.

Preconditioning the signal can be difficult when the characteristics of the propagation channel change rapidly. The channel response can change with time due to the movement of the receiver unit or changes in the environment surrounding the receiver unit. Given a mobile environment, an optimal performance requires that information regarding channel characteristics, such as fading and interference statistics, be determined and transmitted quickly to the transmitter unit before the channel characteristics change significantly. As delay of the measurement and reporting process increases, the utility of the channel response information decreases. A

present need exists for efficient techniques that will provide rapid determination of the channel characteristics.

SUMMARY OF THE INVENTION

The present invention is directed to a method and apparatus for the measuring and reporting of channel state information in a high efficiency, high performance communications system, comprising the steps of: generating a plurality of pilot signals; transmitting the plurality of pilot signals over a propagation channel between a transmitter unit and a plurality of receiver units, wherein the transmitter unit comprises at least one transmit antenna, each of the plurality of receiver units comprises at least one receive antenna, and the propagation channel comprises a plurality of sub-channels between the transmitter unit and the plurality of receiver units; receiving at least one of the plurality of pilot signals at each of the plurality of receiver units; determining a set of transmission characteristics for at least one of the plurality of sub-channels, wherein the step of determining the set of transmission characteristics uses at least one of the plurality of pilot signals received at each of the plurality of receiver units; reporting an information signal from each of the plurality of receiver units to the transmitter unit, wherein the information signal carries the set of transmission characteristics for at least one of the plurality of sub-channels; and optimizing a set of transmission parameters at the transmitter unit, based on the information signal.

In one aspect of the invention, pilot symbols are transmitted on a plurality of disjoint OFDM sub-channel sets. When the pilot symbols are transmitted on disjoint OFDM sub-channels, the characteristics of the propagation channel can be determined through a set of K sub-channels carrying the pilot symbols, wherein K is less than the number of OFDM sub-channels in the system. In addition to transmitting pilot symbols on disjoint sub-channels, the system can transmit a time-domain pilot sequence that can be used to determine characteristics of the propagation

channel. Along with the generation and transmission of pilot symbols, an aspect of the invention is the compression of the amount of information necessary to reconstruct the characteristics of the propagation channel.

BRIEF DESCRIPTION OF THE DRAWINGS

The features, nature, and advantages of the present invention will become more apparent from the detailed description set forth below when taken in conjunction with the drawings in which like reference characters identify correspondingly throughout and wherein:

FIG. 1A is a diagram of a multiple-input multiple-output (MIMO) communications system;

FIG. 1B is a diagram of a OFDM-based MIMO system with feedback of channel state information;

FIG. 1C is a diagram of an exemplary OFDM pilot signal structure that can be used to estimate the channel state information;

FIG. 2 is a diagram that graphically illustrates a specific example of a transmission from a transmit antenna at a transmitter unit;

FIG. 3 is a block diagram of a data processor and a modulator of the communications system shown in FIG. 1A;

FIGS. 4A and 4B are block diagrams of two versions of a channel data processor that can be used for processing one channel data steam such as control, broadcast, voice, or traffic data;

FIGS. 5A through 5C are block diagrams of the processing units that can be used to generate the transmit signal shown in FIG. 2;

FIG. 6 is a block diagram of a receiver unit, having multiple receive antennas, which can be used to receive one or more channel data streams; and

FIG. 7 shows plots that illustrate the spectral efficiency achievable with some of the operating modes of a communications system in accordance with one embodiment.

pure diversity communications mode can be used in instances where the data rate requirements are low or when the C/I is low, or when both are true.

The MIMO communications mode employs antenna diversity at both ends of the communication link and is generally used to improve both the reliability and increase the capacity of the communications link. The MIMO communications mode may further employ frequency and/or temporal diversity in combination with the antenna diversity. The MIMO communications mode, which may also be referred to herein as the spatial communications mode, employs one or more processing modes to be described below.

The diversity communications mode generally has lower spectral efficiency than the MIMO communications mode, especially at high C/I levels. However, at low to moderate C/I values, the diversity communications mode achieves comparable efficiency and can be simpler to implement. In general, the use of the MIMO communications mode provides greater spectral efficiency when used, particularly at moderate to high C/I values. The MIMO communications mode may thus be advantageously used when the data rate requirements are moderate to high.

The communications system can be designed to concurrently support both diversity and MIMO communications modes. The communications modes can be applied in various manners and, for increased flexibility, may be applied independently on a sub-channel basis. The MIMO communications mode is typically applied to specific users. However, each communications mode may be applied on each sub-channel independently, across a subset of sub-channels, across all sub-channels, or on some other basis. For example, the use of the MIMO communications mode may be applied to a specific user (e.g., a data user) and, concurrently, the use of the diversity communications mode may be applied to another specific user (e.g., a voice user) on a different sub-channel. The diversity communications mode may also be applied, for example, on sub-channels experiencing higher path loss.

The communications system of the invention can also be designed to support a number of processing modes. When the transmitter unit is provided with information indicative of the conditions (i.e., the "state") of the communications links, additional processing can be performed at the transmitter unit to further improve performance and increase efficiency. Full channel state information (CSI) or partial CSI may be available to the transmitter unit. Full CSI includes sufficient characterization of the propagation path (i.e., amplitude and phase) between all pairs of transmit and receive antennas for each sub-band. Full CSI also includes the C/I per sub-band. The full CSI may be embodied in a set of matrices of complex gain values that are descriptive of the conditions of the transmission paths from the transmit antennas to the receive antennas, as described below. Partial CSI may include, for example, the C/I of the sub-band . With full CSI or partial CSI, the transmitter unit pre-conditions the data prior to transmission to receiver unit.

The transmitter unit can precondition the signals presented to the transmit antennas in a way that is unique to a specific receiver unit (e.g., the pre-conditioning is performed for each sub-band assigned to that receiver unit). As long as the channel does not change appreciably from the time it is measured by the receiver unit and subsequently sent back to the transmitter and used to precondition the transmission, the intended receiver unit can demodulate the transmission. In this implementation, a full-CSI based MIMO communication can only be demodulated by the receiver unit associated with the CSI used to precondition the transmitted signals.

In the partial-CSI or no-CSI processing modes, the transmitter unit can employ a common modulation and coding scheme (e.g., on each data channel transmission), which then can be (in theory) demodulated by all receiver units. In the partial-CSI processing mode, a single receiver unit can specify the C/I, and the modulation employed on all antennas can be selected accordingly (e.g., for reliable transmission) for that receiver unit. Other receiver units can attempt to demodulate the transmission and, if they have adequate C/I, may be able to successfully recover the transmission. A common (e.g., broadcast) channel can use a no-CSI processing mode to reach all users.

As an example, assume that the MIMO communications mode is applied to a channel data stream that is transmitted on one particular sub-

channel from four transmit antennas. The channel data stream is demultiplexed into four data sub-streams, one data sub-stream for each transmit antenna. Each data sub-stream is then modulated using a particular modulation scheme (e.g., M-PSK, M-QAM, or other) selected based on the CSI for that sub-band and for that transmit antenna. Four modulation sub-streams are thus generated for the four data sub-streams, with each modulation sub-streams including a stream of modulation symbols. The four modulation sub-streams are then pre-conditioned using the eigenvector matrix, as expressed below in equation (1), to generate pre-conditioned modulation symbols. The four streams of pre-conditioned modulation symbols are respectively provided to the four combiners of the four transmit antennas. Each combiner combines the received pre-conditioned modulation symbols with the modulation symbols for the other sub-channels to generate a modulation symbol vector stream for the associated transmit antenna.

The full-CSI based processing is typically employed in the MIMO communications mode where parallel data streams are transmitted to a specific user on each of the channel eigenmodes for the each of the allocated sub-channels. Similar processing based on full CSI can be performed where transmission on only a subset of the available eigenmodes is accommodated in each of the allocated sub-channels(e.g., to implement beam steering). Because of the cost associated with the full-CSI processing (e.g., increased complexity at the transmitter and receiver units, increased overhead for the transmission of the CSI from the receiver unit to the transmitter unit, and so on), full-CSI processing can be applied in certain instances in the MIMO communications mode where the additional increase in performance and efficiency is justified.

In instances where full CSI is not available, less descriptive information on the transmission path (or partial CSI) may be available and can be used to pre-condition the data prior to transmission. For example, the C/I of each of the sub-channels may be available. The C/I information can then be used to control the transmission from various transmit